CHAPTER 9

WOOD PRESERVATION

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1. INTRODUCTION

Wood preservation can be interpreted to mean protection from fire, chemical degradation, mechanical wear, weathering, as well as biological attack. In this chapter, the term preservation is applied more restrictively to protection from biological hazards and the reader is directed to one of several references (Feist and Hon 1984; Hon and Shiraishi, 2000; USDA, 1999) for a more extensive discussion of non-biological aspects of wood protection.

Most people accept that because wood is of biological origin it must be a perishable material. In contrast, man made materials such as concrete and steel are generally considered to be more durable and permanent. The non-durability of wood is often cited as being one of its greatest disadvantages when compared to other building materials. The premature degradation of solid timber and wood-based composite products costs the consumer substantial amounts of money. Indeed in the United States alone the annual financial losses attributed to fungal decay of timber have been estimated to be well in excess of five billion dollars (Lee *et al*., 2004). Estimates of the damage just caused by termites in the United States range from 750-3,400 million dollars, and these estimates can be doubled if the damage caused by other wood-destroying insects and fungi are included (Williams, 1990). Much of this loss is avoidable. The first line of defense is the use of construction techniques that minimize the exposure of wood to conditions that favour biodeterioration. Usually this means keeping it dry. Where such construction is not practical, wood preservation techniques can greatly extend the service life of wood.

The use of preservative chemicals and treated wood has been and still is sometimes criticized on the basis of health or environmental concerns. Ignorance on the part of the treating industry, poor work practices and lax environmental regulation all share part of the blame for that negative perception. Innovation in the first half of the 20th century led to the development of more effective wood protecting chemicals and processing techniques that turned a specialty industry into a commodity business (Preston, 2000). As can happen in all commodity businesses, research and development was not sustained when profit margins began to fall and the door was opened for competitive products such as plastics, concrete and steel.

Some countries, such as New Zealand, have a well established and regulated timber preservation industry and the benefits of construction with treated timber are well appreciated by the public at large. This is not so true of the United States or Europe where treated wood for residential decking and other consumer applications is losing market share to man made materials such as plastics (Clemons, 2002).

The old adage 'familiarity breeds contempt' might certainly be applied to wood preservation in recent years. The construction industry, building code enforcement and the public at large have come to expect extended lifetimes for wood-based building components while forgetting how that longevity is achieved. In New Zealand in 1998 an ill-advised decision to allow untreated house frames coincided with a trend toward monolithic cladding systems which aided by inadequate design/ detailing and coupled with poor construction practices resulted in a 'leaky building' crisis. The failure was in the weather tightness of the external envelope arising from the rigidity of the panels and the movement of the underlying timber, from poor detailing or even the absence of flashings around openings, and in poor performance of jointing materials. This allowed egress of water with no means of drying out any wet elements within the enclosed wall cavity. The problem was systemic, with the way the components were put together rather than poor performance of an identified product. While blame was diffuse the reputation of timber framing suffered. The inference is that timber treatment is not a solitary activity and needs to be seen in the context of building design and construction practices. Preservative treatment should not be used to compensate for loss of eaves, omission of flashings, abuse of sealants, moisture entry into concealed spaces with nowhere to drain *etc*. Sadly the problem has been evident elsewhere, in Canada, the U.S. and Europe.

Moving into the 21st century the wood preservation industry is of necessity facing a major overhaul. Health and safety concerns are being alleviated through a transition to less toxic chemicals. Environmental concerns with preservative treatments are counter-balanced by their ability to extend the durability of wood products, allowing conservation of forest resources. New preservative chemistries have been developed to target specific wood biodeteriogens. While other construction materials could substitute for wood in many applications, such materials are generally more expensive and require more energy to produce (Cassens *et al*., 1995). In that regard, life cycle analysis concepts are being used to promote the virtues of wood preservation (Hillier and Murphy, 2000). Best management practice concepts are also being adopted by the wood preservation industry (Anon., 1996). Wood is no longer being over treated, efforts are being taken to minimize dripping after treatment and surface residues are no longer an issue. Innovative processes and preservative chemistries are being developed to protect wood-based composites such as oriented strand board and medium density fibre board further expanding the universe of wood protection. In short the future for preservative treated wood is a positive one.

2. ORGANISMS THAT DEGRADE WOOD

Depending on where and how they are used, wood products may be attacked by a range of biodeteriorogens that include fungi, insects, marine borers and bacteria.

Fortunately, wood may be protected from biological degradation in a number of ways. The optimal choice depends on the local environment and organisms present. Accordingly, it is important to have some understanding of the biology of these organisms. To do justice to such an interesting topic deserves a dedicated discussion in its own right, but only a brief review of the key points can be provided here. More extensive reviews of the biology of wood-degrading organisms are available (Daniel, 2003; Eaton and Hale, 1993; Highley, 1999; Nicholas, 1973a; Rayner and Boddy, 1988; Zabel and Morrell, 1992).

2.1. Wood inhabiting fungi

Fungi require air, moisture and nutrients in order to invade and colonize wood.

Fungi are micro-organisms that depend on organic matter for nutrients. Above ground and out of soil contact, fungi typically infect or colonize wood either via reproductive spores carried on air currents or in liquid water. Where timber is in contact with the ground or immersed in water it may be infected by fungal spores but more commonly the fungal invasion is in the form of microscopic, threadlike structures each of which is known as a hypha, or collectively as mycelium. Fungi spread within wood only where there is a source of water and where environmental conditions favour growth.

Fungi need adequate moisture, not only to prevent desiccation but also to provide a medium for the outward diffusion of the extracellular enzymes and other degradative systems produced by the fungus and for the movement of mineral nutrients and degradation products in the opposite direction. The optimal moisture condition for decay by the most active rot fungi is above the wood's fiber saturation point where free water is available for the transport of enzymes and nutrients, but also there is plenty of oxygen in the lumens for fungal metabolism. Below 20-22% moisture content infected wood will generally not decay because the fungus cannot grow. However, some fungi may persist for years under dry conditions and if the moisture content later rises above that critical level the fungus may reactivate and attack the wood again.

Fungi are facultative aerobic organisms; they need oxygen to survive. Decay is retarded and may even be completely inhibited by an excess of moisture because it can limit the supply of oxygen needed for fungal respiration. Decay of wood is most severe at or just below the ground line in power poles, fence posts *etc.* for the simple reason that the amount of oxygen and moisture is optimal. As the depth of soil increases the oxygen supply becomes reduced while the moisture content generally increases. Where buried in the ground timber can survive for hundreds of years provided either moisture or oxygen is lacking.

A temperature of 25-30°C is optimal for the growth of most fungi. Below 12°C decay is usually very slow and few fungi are active above 40°C. In general fungi are not killed by low temperature but they are somewhat more sensitive to elevated temperatures. That sensitivity to heat can be utilized to advantage for sterilizing infected wood in a conventional kiln, provided high temperatures are applied for long enough to ensure heating of all infected parts of the wood. Such treatment is

therefore appropriate for timber known to be susceptible to decay or where decay is only at the incipient stage, i.e. the wood is infected but not yet decayed. It is pointless to kiln sterilize even slightly decayed wood as the material will have lost much of its strength, particularly its toughness.

2.1.1. Mould and stain fungi

Mould fungi can be broadly classified as being saprophytic organisms that utilize simple sugars and other carbohydrates derived from cell lumens. Since they do not attack the wood cell wall structure they do not cause significant decreases in wood mechanical properties. Moulds are noticeable as fuzzy or powdery growths with colours ranging from white to black. They primarily affect the aesthetic appearance of the wood.

Unfortunately, to the layman all or any fungal growth associated with sawn or round wood is of considerable concern. Not only is there a misconception that the structure is in danger of premature collapse but in extreme cases hysteria ensues out of concern about exposure to mould spores (Uzonovic *et al*., 2003). Moulds can cause allergic or asthmatic reactions in some sensitive people and a few moulds produce potentially toxic substances; however anything more serious than allergic or irritant symptoms is rare.

Sapstain fungi are similar to mould fungi, with the primary distinction being on the depth of the discolouration in the wood. Sapstain results where fungi with pigmented hyphae grow within the sapwood which can become badly discoloured as a result. As with the moulds these fungi derive their nourishment principally from cell contents, and therefore attack parenchyma-rich ray tissue. As a result the discoloured wood in softwoods is often wedge-shaped when seen in cross section, although in hardwoods a more diffuse staining distribution may result. This discolouration can be unsightly and is undesirable under natural finishes. Sapstain fungi are also significant because their hyphae can break down pit membranes and make fine holes as they pass through cell walls. This increases wood permeability and can create a number of problems when the wood is used. It makes the timber more susceptible to rewetting which in turn favours decay and if the wood is treated it can lead to over treatment and subsequent bleeding of the excess preservative in service. Sapstain fungi grow best in warm, moist conditions and so are particularly common in the wet tropics, especially as suitable insect vectors are very numerous.

If harvesting and milling is undertaken efficiently a prophylactic dip or spray immediately after sawing may provide the necessary short term protection against mould and sapstain during seasoning, storage or export.

Mould fungi can sometimes be a problem in preservative treated wood during prolonged storage especially if the wood is prevented from drying quickly after treatment. While this might seem counterintuitive because the wood is preservative treated in reality many mould fungi are not susceptible to the same preservative chemicals that are effective against decay fungi, To address this problem, preservative formulations may include mouldicide additives to provide short term protection against mould growth.

2.1.2. Decay fungi

Decay is the most destructive form of fungal attack on wood and occurs in three forms that are generally described as brown, white and soft rots. The terminology relates to the physical appearance of the wood after it has been extensively attacked. Brown and white rots result from the growth of highly specialized higher fungi (of the *Basidiomycotina*). The hyphae of Basisdiomycetes are able to ramify through the three-dimensional structure of wood creating large bore holes in the cell walls. These fungi utilize extracellular enzymes to degrade the wood cell walls to derive their nourishment. Under optimal conditions the process quickly weakens infected areas. Soft rot is caused by another group of higher fungi (*Ascomycotina* and many *Deuteromycotina*) which produce fine bore holes without the extensive enlargement seen with the Basidiomycetes.

Brown rots are more commonly associated with softwoods. The fungi attack primarily the cell wall carbohydrates (cellulose and hemicelluloses) and change the structure of lignin only slightly. As a consequence, the decayed wood develops a brown colour that will eventually exhibit extensive cubical cracking as it dries. Dry rot (a particular form of brown rot caused principally by *Serpula lacrymans*) is so-called because it is capable of colonizing, transporting water to and subsequently destroying sound, initially dry wood. The fungi can wet wood by transporting water over considerable distances along macroscopic root-like structures formed by aggregations of hyphae. In many respects the use of the word ‘dry’ is a misnomer because the wood was in fact moistened at some point and subsequently dried after decaying, creating the illusion that dry rot occurred (Bech-Andersen and Elborne, 1999).

White rot affects both softwoods and hardwoods. Cellulose, hemicelluloses and lignin are degraded. Progressive erosion by hyphae in the cell lumen as well as bore holes weaken the cell walls. Wood affected by white rot may darken in the early stages of decay but as the decay advances bleaching may occur. It does not split into cubical fragments but, because the breakdown of the lignin weakens interfibre bonding, the wood becomes spongy or stringy in texture.

Soft rot is a form of decay caused by a quite different group of fungi that is more closely related to moulds. They usually attack wood in wetter conditions than those favoured by brown and white rot fungi. Soft rot fungi characteristically attack the surface of the wood, gradually eroding inward at the rate of a few millimetres per year. The principal distinguishing microscopic feature of soft rot is the production of chains of geometrically shaped cavities oriented with their long axis following the microfibrils of the cell wall layer in which they are located, typically in the S_2 layer. Generally these cavities are cylinders with biconical ends or they are diamond-shaped. In many hardwoods an additional form of attack occurs with erosion of the cell wall lumen surface caused by hyphae. In softwoods erosion may be less severe because the S_3 layer is more developed and more highly lignified.

Soft rot is of economic significance mainly under conditions that retard or inhibit the activities of brown and white rot fungi, e.g. in preservative treated wood, in thermophilic situations and aquatic environments. This slow and initially superficial rot is sometimes more significant than might appear at first sight for several reasons:

- The outerwood contributes disproportionately to the bending strength of timber e.g. in a stressed pole or corner post.
- In some species heartwood is attacked as rapidly as sapwood.
- Many of the fungi involved are tolerant of high levels of commonly used wood preservatives.

2.2. Wood destroying insects

Wood destroying insects are of major significance in most regions of the world, although the number of species involved is relatively small (Creffield, 1996; Lenz, 2002). They damage wood by chewing it with their mandibles, although in many cases they derive no direct nourishment from it. For some, such as longhorn borers, only the insect larvae tunnel within the wood; in other cases, such as pinhole borers, all stages occur there. From a wood durability perspective, insect attack is less predictable than decay because some insects can bore into sound dry wood, and because insect populations are not uniformly distributed. However, most insects are similar to fungi in attacking only moist wood.

In the natural environment most wood decomposes as a result of both insect and microbial activity. Most insect pests of wood are either termites or beetles. Other insects such as wood wasps, moths, carpenter ants *etc*. are sometimes significant locally but by and large the termites (order *Isoptera*) and beetles (order *Coleoptera*) are the wood destroying insects of greatest importance.

2.2.1. Termites

All termites feed on cellulosic materials (Creffield, 1996). The most important are the subterranean termites that are found throughout the world within 40-45° of the equator. The number of species and total termite biomass increases nearer the equator, and they are generally regarded as a more serious threat in tropical and sub-tropical regions. Like all *Isoptera*, subterranean termites are social insects that live in colonies that are established in the soil. In their quest for food, subterranean termites may enter buildings and other above ground structures through enclosed galleries which they construct to protect themselves from desiccation and which connect to the soil and ultimately to the colony. Once inside a piece of wood, termites tunnel along the grain often leaving only a thin shell of sound wood to conceal their activities. Traditionally wooden structures have been protected by treating the soil under and around the building with an insecticide: subsequent soil treatments are necessary to maintain protection. Physical barriers such as metal caps between building and foundation supports have some limited value in that they force the colony to construct an enclosed gallery across both faces of the cap and thereby warn the home owner of their presence. Soil barriers such as graded gravel and steel mesh show some promise, as do toxic bait systems (Lenz and Runko, 1993). The bait systems use slow acting insecticides, allowing foraging termites to return to the nest to feed the colony (Su and Scheffrahn, 1991). Building with preservative treated timber provides another layer of protection if other protection mechanisms fail.

Drywood termites are the other group which sometimes attack wooden structures. They do not require access to soil as the queen actually invades the wood and her progeny become established there. Fortunately, such colonies are rarely as large as those of subterranean termites so that the damage is seldom as extensive. Where they occur they are nevertheless a serious pest and control measures are required. The best control is achieved by using preservative treated wood.

2.2.2. Wood boring beetles

The beetles infesting wood fall into three groups:

- Bark beetles and the related pin hole borers.
- Other beetles found in green wood.
- Borers found in dry wood (<25% moisture content).

A few species of bark beetle and pin hole borer are able to attack live trees, but most species prefer to invade green logs or stumps after felling. Wood damaged by bark beetles is largely discarded in slab wood. In lumber, the loss of strength associated with the 'holes' is minimal and the impact largely cosmetic. However these insects sometimes carry sapstain fungi that can result in very visual aesthetic degrade. Many other beetles such as flat-headed borers can infest green logs and timber but usually do not cause extensive damage in wooden structures. Under normal circumstances the wood is removed from the forest, processed and dried too quickly for these insects to have much effect.

The most destructive beetle pests are those which attack seasoned wood in service, e.g. *Anobium punctatum*, *Hylotrupes bajulus*, *Lyctus brunneus*. Only a few species are capable of doing this, but those that do can cause serious problems. They include long-horn beetles, the common house borer or furniture beetle and powder post beetles. Given susceptible lumber and suitable conditions for development, all of the above insects are difficult and expensive, or in some cases impossible, to control. The use of preservative treated wood obviates the necessity for control.

2.2.3. Marine borers

Marine borers damage wood structures in salt or brackish water throughout most of the world, although the severity of attack generally increases in warmer waters. The most damaging marine boring organisms are shipworms, pholads and gribbles.

Shipworms, i.e. *Bankia* and *Teredo* spp., are molluscs. Their minute free-swimming larvae move around until they lodge on the timber surface prior to gaining entry. Once within the timber they proceed to elongate and grow as they tunnel through the wood creating an extensive honeycombed structure: superficially the timber appears sound. Treatment with creosote or with waterborne preservatives containing copper and arsenic can protect wood from shipworm attack.

Pholads are clam-like molluscs i.e. *Martesia* or *Xylophaga* that create pear-shaped cavities near the surface of the wood. Pholads are limited to warmer waters,

and can cause severe problems in tropical ports. Pholads also have some resistance to copper and arsenic based wood preservatives.

By contrast gribbles, i.e. *Limnoria* spp., are small crustaceans that attack the surface of the wood, and tunnelling seldom extends far from the surface. The combined action of water movement, gribble and microbial attack effectively wears away the wood. Damage is concentrated on exposed timber between low and high tide. Related crustaceans (*Sphaeroma* spp.) are somewhat larger than *Limnoria* and have a similar attack pattern: however, *Sphaeroma* spp. are less numerous and less damaging than *Limnoria* spp. In warm waters a species of Limnoria (*Limnoria tripunctata*) is able to attack creosote treated wood. A more detailed discussion of marine borer biology can be found in Cragg (2003) or Distel (2003).

3. NATURAL DURABILITY

Although sapwood is rarely durable, the heartwood of many tree species exhibits some degree of resistance to attack by decay fungi and insects (Table 9.1). This natural durability can be attributed to a combination of toxic extractives present in the wood and low inherent permeability. As a result of this natural durability such woods can be used outdoors and in some cases in ground contact or submersed in water. Wood from naturally durable species is sometimes viewed as being environmentally preferable to chemically treated wood, and many of these species have an attractive appearance. In addition, some species such as black locust, greenheart and ipe also have excellent strength properties (Green *et al*., 1999). As might be expected such a combination of desirable attributes has led to increasing interest in use of durable species from the tropical countries for construction in North America and Europe. However, several factors limit the use of naturally durable species. In developed countries the volume of growing stock of naturally durable species is relatively low compared to the demand for durable wood

Table 9.1. Natural heartwood durability of certain timbers in ground contact, based on 50 × 50 mm stakes: indicative figures only. Hardwoods (HMSO, 1969); softwoods (Hughes, 1982).

Perishable (<5 yrs)	Non-durable (5-10 yrs)	Moderately durable (10-15 yrs)	Durable (15-25 yrs)	Very durable (>25 yrs)
Hardwoods				
Alder	Elm	Keruing	Kempas	Afrormosia
Beech	*Eucalyptus regnans*	Sapele	Meranti	Iroko
		Seraya, red	Oak	Teak
Birch	Obeche			
Poplar, black	Seraya, white	Sepetir		
Ramin				
Softwoods				
Corsican pine	Douglas fir	*Cupressus macrocarpa*		*Podocarpus totara*
Ponderosa pine	European larch			
	Radiata pine	Redwood		
	Western red cedar	Sitka spruce		

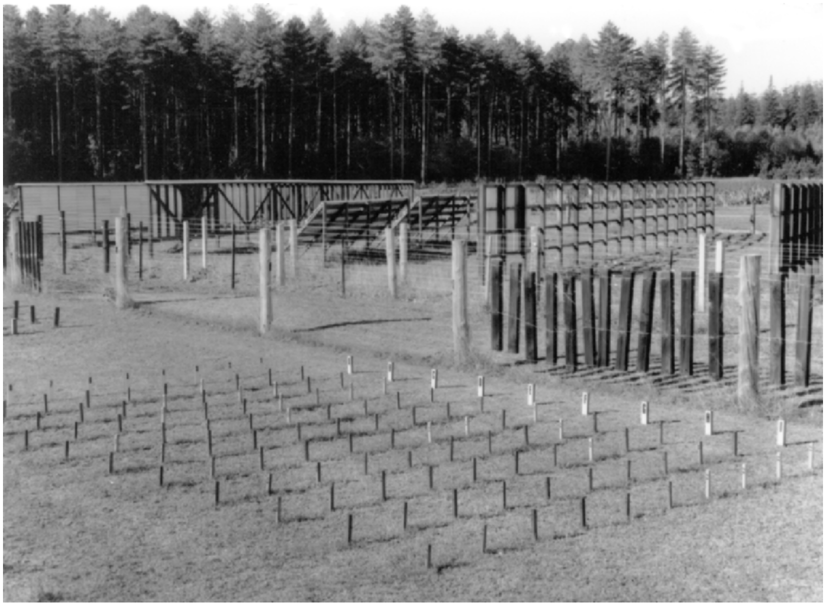

Figure 9.1. Field tests, also known as graveyard trials, as used to establish the durability of untreated heartwood of various timbers and also to determine the effectiveness of a variety of preservative systems (unpubl. courtesy New Zealand Forest Research Institute).

products. The felling and export of tropical species from developing countries to industrialized nations raises concerns about exploitation, deforestation and destruction of habitat. On the other hand, woodlots of fast growing species such as black locust *Robinia pseudoacacia* and some eucalypts whose heartwood is rated moderately to very durable may be a viable proposition for on-farm commodities such as posts and rails and even for simple farm buildings. Elsewhere durable heartwood is a scarce commodity.

While the durability of many species has been evaluated with post or stake tests (Figure 9.1), evidence for durability of other species is largely anecdotal. A comprehensive review by Scheffer and Morrell (1998) has helped to collate the literature related to durability for a wide range of wood species. Further, usage is also limited by variability in durability. For some species there are wide differences in heartwood durability between adjacent trees and even between boards cut from the same tree. Also boards can contain both sapwood and heartwood as it is often not economic or practical to cut timber so as to exclude all sapwood. Thus only broad estimates of durability can be developed (Table 9.1). As a result of these sources of variability the use of naturally durable species is often restricted to above-ground applications where the biodeterioration hazard is lower and the consequences of an early failure are less severe.

Very few wood species have sufficient natural durability to allow their use in marine environments without additional protection. Two species that have provided

excellent performance as marine piles are turpentine (*Syncarpia glomulifera*) from Australia and greenheart (*Ocotea rodiaei*) from Guyana. The uncertain supply and the high cost of naturally borer-resistant timbers has led to the successful development of a marine construction industry throughout the world that relies on preservative treated wood.

One should state the obvious. Naturally durable timbers contain various extractives that are able to inhibit decay, so one should expect some of these timbers to have the potential, at the very least, of inducing allergic reactions in people that handle and process them (Woods and Calnan, 1976).

Finally, there are numerous instances of wood remaining in sound condition for hundreds and even thousands of years, but this is usually a result of construction practices and favorable environmental conditions. Norwegian Stave Churches have survived from the early Middle Ages because for much of the year the air is dry and very cold (being below freezing for up to eight months) while in summer it is hot, the relative humidity is low and the level of ultraviolet radiation is high. These structures also benefited from designs that minimized trapping of moisture and that kept timber out of ground contact.

4. PHILOSOPHY OF PROTECTION

During the nineteenth century the demand for durable construction particularly for rail road tracks and bridges so necessary for the industrial revolution, the scarcity of naturally durable timbers and an inability to control and regulate the immediate environment led to the development of a timber preservation industry (Freeman *et al.*, 2003). Spurred on by initial successes it was surmised that provided the timber, the preservative and the treatment process were all appropriate, it should be possible to ensure that treated timber retains its integrity for as long as is desired. In practice wood is exposed to a wide spectrum of hazards that vary with end-use, geographic location, and construction practice. It was soon recognized that no single preservative treatment was optimal for all situations. It is inappropriate to use a high concentration of a relatively toxic preservative for applications such as millwork where a lower concentration of less toxic preservative would provide an adequate service life. Similarly, a water-soluble preservative such as a borate that may provide excellent protection for wood used indoors will not provide long-term protection for wood used outdoors. Again, some preservatives are effective in preventing attack by fungi but not insects. Others may offer little protection against mould fungi. Failure to put the potential hazards into perspective tended to create uncertainty with the result that preservative treatments used were stronger than necessary. Today, increasing emphasis is placed on using preservatives that are targeted more specifically to particular applications (Goodell *et al.*, 2003). Such preservatives are safer to use and potentially less damaging to the environment.

A key but vexing question in any consideration of the philosophy of wood preservation must be how long a piece of treated wood should last. It is apparent that no one specific time frame exists.

The efficacy of a preservative treatment in wood is a function of:

- Type of organisms present and environmental conditions.
- The preservative's intrinsic toxicity to or efficacy against the target organism(s).
- The preservative's ability to resist leaching, UV degradation or other forms of environmental degradation.
- The degree of penetration and uniformity of distribution of preservative within the treated wood.
- The retention, or concentration, of the preservative within the treated wood.

In recognition that the deterioration hazard varies with end-use, many countries have developed 'hazard class' or 'use category' systems that specify those preservative formulations that are suitable in particular situations, the amount of preservative to be used (its 'retention'), and the depth to which the preservative must penetrate the wood (Morrell and Preston, 1995) (Table 9.2). As might be expected there is considerable overlap between these end-use categories.

Table 9.2. General guidelines for the specification of treated timber.

End use, relative hazard	Principal hazard	Choice of timber	Condition of timber	Choice of preservative	Quantity of preservative uptake	Treatment process
Marine	Marine borers	Hardwood or softwood	Incised or otherwise modified	Oil or water based	High or low chemical uptake	Pressure treatment
Ground contact	Fungi	Permeable or impermeable	Treat dry or green	Environmental hazard level: broad toxicity	Deep treatment or envelope	Sap Displacement
Exposed exterior	Fungi/ insects	Wide or narrow sapwood band		Fixed or leachable		Vapour phase
Interior of buildings	Wood-boring insects			Clean or staining		Diffusion

Wood preservatives are generally classified or grouped by the type of application or exposure environment in which they are expected to provide long term protection. Some preservatives have sufficient leach resistance and broad-spectrum efficacy to protect wood that is exposed directly to soil and water. These preservatives will also protect wood exposed above ground, and may be used in those applications with lower retentions (lower concentrations in the wood). Yet other preservatives have intermediate toxicity or leach resistance. This allows them to protect wood that is fully exposed to the weather, but not in contact with the ground. Other preservatives lack the permanence or toxicity to withstand continued exposure to precipitation, but

are effective with occasional wetting. Finally, there are formulations that are so readily leachable that they can only withstand very occasional, superficial wetting.

It is not possible to evaluate a preservative's long term efficacy in all exposure environments. Preservatives have been tested most extensively in ground contact only, and there is no perfect formula for adjusting or predicting how well a wood preservative might perform in another situation. This is especially true for above-ground applications. To compensate for this uncertainty, there is a tendency to be conservative when selecting a preservative for a particular application.

5. PRESERVATIVE FORMULATIONS

Historically, wood preservatives have been thought of in terms of their solubility in either water or oil-type solvents (Ibach, 1999). Thus we have so called oil-borne and water-borne preservative systems. More recently that classification has become less relevant, because, with advances in formulation chemistry active ingredients can be formulated with either type of solvent, while others may be emulsions or suspensions. Water-based preservatives often include some type of co-solvent such as an amine or ammonia to keep one or more of the active ingredients in solution. Each solvent has advantages and disadvantages depending on the application.

Oil-type systems in medium to heavy oils are among the oldest and most effective preservatives. These systems usually leave the wood surface dark brown in colour although some lighter solvents can minimize colour changes. Oil-type systems are widely believed to reduce checking and splitting, although this can be difficult to document (Ibach, 1999). Oil-type preservatives are commonly used for applications such as utility poles, bridge timbers, railroad ties and piling. They are less likely to be used for applications that involve frequent human contact or for inside dwellings because they may be oily or have a strong odour.

Water-based preservatives are often used where cleanliness and paintability of the treated wood are required. Typically, wood treated with a water-based preservative has little or no odour when compared to oil-based preservatives. However, unless supplemented with a water repellent, the water-based systems do not confer any dimensional stability to the treated wood. In addition, water-based preservatives that utilize copper as a fungicide may not adequately protect hardwood species under conditions that favour soft rot attack. Some water-based preservatives can increase the rate of corrosion of mild steel fasteners.

The original water-based preservatives were simple salts, e.g. $ZnCl_2$ and NaF, but it was found that they had a tendency to leach out when exposed to liquid water and so were unsuitable for many exterior situations. Some recent preservatives are initially soluble in acidic or alkaline solutions but after pressure impregnation they are designed to chemically bind or 'fix' with the wood or form insoluble compounds. These are versatile preservatives. By varying the solution strength or the treatment process the amount of chemical deposited in the wood, i.e. the retention, can be adjusted according to the degree of hazard likely to be encountered in service. The lowest retentions are used to combat insect attack and the highest are used against marine borers.

Copper has been a primary ingredient in wood preservative formulations for over a century because of its excellent broad-spectrum fungicidal properties, low

mammalian toxicity and relatively low price (Evans, 2003). A few fungi are tolerant of high levels of copper (Barnes, 1995; Choi *et al*., 2002), and under some unusual circumstances copper treated wood exposed to copper tolerant fungi can decay faster than untreated wood placed in the same environment. The existence of 'tolerant' fungal species is not confined to copper. Fungal species tolerant to arsenic and creosote are well known. Preservative formulators will often include a co-biocide to provide further protection against such tolerant species.

Historically, chromated copper arsenate (CCA) has been the most widely used water-borne treatment. CCA is a mixture of chromic acid, cupric oxide, and arsenic pentoxide. CCA is strongly fixed to the wood and for the last 70 years has provided excellent protection in a variety of environments. The primary drawback to CCA is the perceived human health concerns associated with arsenic and hexavalent chromium: both are recognized as potential human carcinogens. As a result of these concerns CCA is no longer available for use in a number of countries, and its usage is severely restricted in others (Freeman *et al*., 2003). Non-chrome, non-arsenic alternatives to CCA have been developed and several of these alternatives have gained wide commercial acceptance. For the most part the alternatives still rely on copper as the primary biocide, but the chromium and arsenic has been replaced with other components. In some places, particularly in Europe, even copper is coming under environmental scrutiny. In Europe there has been considerable interest in developing wood preservatives that do not contain copper or other heavy metals (Goodell *et al*., 2003). Such preservatives must of necessity depend on combinations of relatively low toxicity organic fungicides and insecticides originally screened for agricultural uses. Developing new wood preservative systems presents technical difficulties because bacteria or other non-wood attacking organisms may degrade these organic compounds. This challenge is particularly acute where wood is in contact with the ground.

Each preservative has unique characteristics that might affect its suitability for a particular application. These include factors such as appearance, odour, toxicity, wood species compatibility and availability. The discussion that follows provides a basic background to a wide range of preservative systems. Some of these systems are still in use today, while others have been phased out and others are currently under development. Further discussion of preservative systems can be found elsewhere (Ibach, 1999; Nicholas, 1973b; Richardson, 1993; Schultz and Nicholas, 2003). It will be readily apparent from this section that the transition away from traditional heavy metal broad spectrum biocidal compounds to organic chemistries has added significant complication to the wood preserving industry as a whole.

5.1. Preservatives used in marine environments

Marine borers present a severe challenge. Some preservatives that are very effective against decay fungi and insects do not provide protection in seawater.Thus, despite severe reservations about the continued use of creosote and CCA these remain the only viable treatments currently available. Creosote is most commonly used, preventing attack by all marine borers except *Limnoria tripunctata*.

Waterborne preservatives containing copper and/or arsenic such as CCA have also proved to be efficacious either alone or in combination with creosote. Waterborne preservatives such as CCA or ACZA protect against attack by shipworms and *Limnoria* spp, but they do not protect against pholads.

Much higher preservative retentions are required to protect against marine borers than are needed to protect wood in terrestrial or fresh water applications. Further, with no single preservative effective against all marine borers, more expensive dual treatments involving an initial treatment with a waterborne preservative followed by a conventional creosote treatment may be required in some locations.

Physical barriers such as plastic sleeves or wraps have been used to protect piling, but they are vulnerable to breaches arising from mechanical damage. These are most effective when applied to pressure preservative treated piles.

5.2. Heavy duty preservatives designed for use in high deterioration hazard areas

Soil contact and fresh water immersion applications present a high deterioration hazard to wood and wood-based products. Preservatives used in these environments must exhibit sufficient toxicity and leach resistance to protect the wood for the intended lifetime of the building or structure, as building components in such environments typically have a structural or support function and can be difficult to replace *in situ*. The preservative's active ingredients should penetrate deep into the wood for maximum performance. Thus, almost without exception, only pressure treated materials find their way into high deterioration hazard end uses.

Broad-spectrum biocides with relatively high retention levels are the preservatives of choice. The sections that follow are not intended to be all inclusive rather they provide a brief summary of the major historically important systems and the products currently in use around the world.

5.2.1. Coal-tar creosote

Creosote is the oldest 'modern' wood preservative. It is formulated by fractionating coal tar distillate that in turn is a by-product of high temperature carbonization of coal. Creosote is a complex mixture of polycyclic aromatic hydrocarbons (PAHs), tar acids and tar bases that makes it such an effective broad-spectrum preservative. Difficult-to-treat woods can be pressure impregnated with hot creosote for lengthy periods. The wood has improved dimensional stability. However treated wood sometimes bleeds and has an oily surface, so it is not the first choice for applications where there is a high probability of human contact. Workers may dislike creosote treated wood as it soils their clothes and on contact photosensitises the skin.

Creosote treated wood has a lengthy record of satisfactory use in a wide range of industrial activities – as telegraph poles, on wharfs and with the railroads. Treating facilities using creosote are widely distributed in many parts of the world, making it one of the more readily available preservative treatments. The ease with which workers can climb creosote treated wooden utility poles is a significant advantage.

Concern over toxicity of creosote has limited or curtailed its use in many places.

5.2.2. Pentachlorophenol (PCP) in heavy oil

PCP was first introduced in the 1940s as a substitute for creosote. The active ingredient, a chlorinated phenol, is a crystalline solid that dissolves in a variety of organic solvents. The performance of PCP and the properties of the treated wood are influenced by the choice of solvent. A heavy oil solvent is preferred where treated wood is to be used in ground contact – wood treated with lighter solvents is not as durable. PCP treated wood has many characteristics and properties that mimic those of creosote, except that it is ineffective against marine borers.

Long-standing concern about broad and persistent toxicity (from contaminants) has curtailed the use of PCP in many countries and severely restricted use elsewhere.

5.2.3. Chromated copper arsenate (CCA)

CCA, developed in the 1930s, was once by far the most commonly used of all wood preservatives and until very recently represented over 90% of the sales of waterborne wood preservatives in the United States – as the preservative of choice for most ground and marine applications. There were numerous formulations with varying ratios of copper, chromium and arsenic. One of the most common formulations is 47.5% chromium trioxide, 18.5% copper oxide, and 34.0% arsenic pentoxide dissolved in water (CCA Type C). Typical retentions of active elements are several kilograms per cubic metre of wood, with yearly production of around 20 million cubic metres in the mid-1990s (Clausen and Smith, 1998).

CCA has decades of proven performance in field trials and in-service. With the correct species and treatment CCA provided an assured in-ground service life in excess of 50 years. Recently Bull (2001) has proposed that the fixation products of CCA are dominated by chromium (III) arsenate, chromium (III) hydroxide and wood-carboxylate-copper (II) complexes. CCA is potent precisely because it is bioavailable – and persistent. Significantly the separation of copper from chromium and arsenic is consistent with the observation that acetic acid and chelating organic acids – and silage or compost – under certain circumstances can promote leaching and early failure (Cooper and Ung, 1995; Kazi and Cooper, 1998).

With difficult-to-treat species it may be hard to obtain adequate penetration. There is an upper limitation to the temperature during impregnation and the rapid reaction of chromium within the wood structure can hinder penetration during longer pressure periods.

Today CCA is longer used in most jurisdictions; elsewhere its use is severely restricted. However, for accelerated testing, CCA is still the reference preservative used to evaluate the performance of other waterborne wood preservatives.

5.2.4. Copper naphthenate in heavy oil

The efficacy of copper naphthenate has been known since the early 1900s, and various formulations have been used commercially since the 1940s. It is an organometallic compound formed as a reaction product of copper salts and petroleum derived naphthenic acids. Like pentachlorophenol, copper naphthenate

can be dissolved in a variety of solvents, but is more durable when dissolved in heavy oil. Although not as widely standardized as creosote and PCP treatments, copper naphthenate is used increasingly in the treatment of utility poles.

More generally, it is recommended for field treatment of cut ends and drilled holes (that expose untreated wood) made during construction using pressure treated wood. With the right solvent and treatment procedure, it is possible to paint copper naphthenate treated wood after it has been allowed to weather for a few weeks.

Copper naphthenate has been formulated as a water-based system, and sold in this form for consumer use. The waterborne formulation minimizes concerns about odour and surface oils. Water-based formulations are not used in pressure treatment.

5.2.5. Acid copper chromate (ACC)

ACC is an acidic water-based preservative currently in limited use in Europe but at the time of writing is under a no sell regulatory moratorium in the United States. It was originally developed in the 1920s but could not compete effectively with CCA on either price or performance so was largely relegated to small niche markets such as cooling tower components. ACC contains 31.8% copper oxide and 68.2% chromium trioxide. The treated wood has a light greenish-brown colour, and little noticeable odour. Tests on stakes and posts exposed to decay and termite attack indicate that wood well-impregnated with ACC gives acceptable service. However it is susceptible to attack by copper-tolerant fungi, and because of this its use has largely been limited to above-ground applications. It can be difficult to obtain adequate penetration of ACC in some of the more refractory wood species such as white oak or Douglas fir. Since it does not contain arsenic ACC is perceived to offer certain environmental and handling advantages over CCA. However, from a practical perspective the arsenic is replaced by a higher proportion of hexavalent chromium. In principle the hexavalent chromium should be converted to the more benign trivalent state during treatment and subsequent storage of the wood but recent unpublished studies seem to indicate that the time frame for full conversion is exceedingly long. Given the potential for the product to expose consumers to hexavalent chromium it seems unlikely that acid copper will receive widespread acceptance in the United States except perhaps for industrial applications where human contact is minimal.

5.2.6. Ammoniacal copper zinc arsenate (ACZA)

ACZA or Chemonite® is a water-based preservative containing copper oxide (50%), zinc oxide (25%) and arsenic pentoxide (25%). It is a refinement of an earlier formulation, ACA, that is no longer available. The ammonia in the treating solution, in combination with processing techniques such as steaming and extended pressure periods, allow ACZA to obtain better penetration of difficult-to-treat species than many other water-based preservatives. Treating facilities using ACZA are currently located in western United States, where many of the native timbers are difficult to treat with other waterborne preservatives. The primary biocidal activity can be

ascribed to both the presence of copper and arsenic although zinc exhibits some fungicidal properties.

5.2.7. Copper-chromium-boron (CCB) and copper-chromium-phosphate CCP

CCB and CCP are similar in many respects to CCA except for the fact that the arsenic is replaced by boron in CCB and by phosphate in CCP. Most commonly used in Europe, both formulations were developed in part to address concerns about the toxicity of the arsenic in CCA. CCB and CCP are less efficacious than CCA and in the absence of arsenic the fixation processes are compromised. The systems still contain significant levels of chromium, which faces significant regulatory pressure from the Biocidal Products Directive in Europe. In the longer term the future for preservative formulations containing chromium is questionable.

5.2.8. Alkaline copper quat (ACQ)

ACQ is one of a number of recent water-based preservatives developed to address environmental concerns about the use of arsenic and chromium in treated wood. Several formulations of ACQ have been developed and marketed but all share a similar composition. The active fungicide and insecticide components in all ACQ formulations are copper and the quaternary ammonium compounds ('quats'). Copper provides the primary fungicide and insecticide activity in ACQ formulations, while the quaternary ammonium compounds ('quats') provide additional protection against copper tolerant fungi and insects. The type of quat may vary as can the copper-to-quat ratio in the formulation. The copper solublilizing agent may be ammonia in ACQ type B or ethanolamine in ACQ types C or D. Alkaline formulating agents, particularly ammonia, have the ability to swell wood cell walls and so improve the penetration of chemicals into wood. This characteristic has proved useful for improving the treatment of the refractory timbers such as Douglas fir prevalent on the West Coast of the United States.

At the time of writing ACQ based technology has secured the lion's share of the wood preservative market in Canada and the United States.

5.2.9. Copper azole

Copper azole is another recently developed water-based preservative formulation that relies primarily on copper solubilized in ethanolamine and an organic trizaole co-biocide. The first copper azole formulation developed contained 49% copper, 49% boric acid, and 2% tebuconazole. More recently, a formulation containing 96% copper and 4% tebuconazole has been used. As with ACQ formulations the copper in copper azole systems provides the primary fungicide and insecticide activity. The azole component provides protection against copper tolerant fungi.

Copper azole has gained widespread use in Europe, North America, Australia and New Zealand.

5.2.10. Copper HDO

Copper HDO is an amine copper water-based preservative that has been used in Europe and is currently is being registered for use as an above ground wood preservative in the United States. The active ingredients are copper oxide, boric acid, and copper-HDO (Bis-N-cyclohexyldiazeniumdioxy copper). The appearance and handling characteristics of wood treated with Copper HDO are similar to the other amine copper-based treatments. It is also referred to as copper xyligen.

5.3. Preservatives used above-ground and fully exposed to the weather

In volume terms the majority of preservative treated wood is used above ground – not in contact with soil or immersed in water. Typical examples might be residential decking or fencing. Logically the heavy duty preservatives mentioned in the last section can also be expected to perform well above ground and many are in current commercial use for that purpose, albeit with a reduced retention of active ingredient.

In many respects a ground contact or fresh water immersion environment represents a very consistent and high exposure hazard: the same cannot necessarily be said of all above ground applications. In certain situations, for example where moisture or organic debris can collect, the above ground environment may present a deterioration hazard similar to a ground contact exposure. This can be particularly problematic to the wood preservative formulator and treater. Here, the heavy duty preservatives discussed in the previous section may be more appropriate for such applications, especially in critical structural members.

Most of the preservatives listed here have not demonstrated the ability to provide long-term protection against a broad range of decay organisms in high decay hazard applications. However, they provide adequate protection for wood that is above ground and occasionally exposed to wetting. Examples of such use include members that may be subjected to wetting from wind-blown rain or from splashing during heavy rainfall, such as millwork. Many applications in this category involve dwellings or inhabited structures for which there has been a steady move in the past few decades to use preservatives with low mammalian toxicity.

There is an increasing move way from treating millwork *etc.* using light solvent carriers because of economic and environmental concerns. The attraction of such solvents was in the dimension stability of the product – no need to redry and remachine – so dressed final product could be so treated. More recently one of the larger millwork producers in the United States successfully developed and marketed millwork components that are pressure treated with a waterborne formulation containing a water repellent emulsion. Rough sawn timbers are treated, dried and then machined into profiles suitable for millwork components. The machined waste can be recycled to make preservative treated wood composite door cores.

In this category the distinction between oil and water-based preservatives has been blurred, as many of these components can be delivered either with solvents or micro-emulsions. The triazole fungicides, such as tebuconazole and propiconazole are being used more widely. Other azoles, including cyproconazole and azaconazole are used in more limited quantities.

5.3.1. Oxine copper (Copper-8-quinolinolate)

Oxine copper is an organometallic preservative comprising 10% copper-8-quinolinolate and 10% nickel-2-ethylhexoate that offers protection against sapstain and moulds. It has low mammalian toxicity. The treated wood has a greenish brown colour and little or no odour. Of particular interest, when used alone it is permitted by the U.S. Food and Drug Administration for treatment of wood used in direct contact with food.

It dissolves in a range of hydrocarbon solvents, but provides much longer protection when delivered in heavy oil. Oxine copper is sometimes used for treatment of the above-ground portions of wooden bridges and deck railings, protecting against both fungi and insects. Adequate penetration of difficult-to-treat species can be achieved, despite the treatment solution being somewhat heat sensitive, which limits the use of heat to increase preservative penetration. Oilborne oxine copper does not accelerate corrosion of metal fasteners relative to untreated wood.

However oxine copper is not widely used by pressure treatment facilities.

5.3.2. Tributyltin compounds

A number of related chemistries belonging to the tributyl tin family of compounds e.g. Bis (tri-n-butyltin) oxide (TBTO) and Tributyl tin naphthenate (TBTN) have been used as wood preservatives. They are colourless to slightly yellow liquids that are soluble in organic solvents, but insoluble in water. They have proved to be most efficacious as anti-fouling agents in marine paints (to be phased out completely by 2008), as preservatives in paint finishes, and in dip treatments for wood used in millwork. Used alone, tributyl tin is not effective in protecting wood used in ground contact, but it can protect wood products that are above-ground and partially exposed to the weather. While cost effective TBTO use has declined steadily due to concerns about the environmental and health effects of tin.

5.3.3. Triazoles

The development costs of biocide ingredients are exceedingly high. Most of the currently available organic fungicide and insecticide compounds being used as wood preservatives and those being considered for future wood preservative applications can trace their origins back to agricultural use. The triazole family of compounds is a good example of this process in action. Some of the more widely used triazoles include propiconazole and tebuconazole. They tend to be sparingly soluble in water but reasonably soluble in light organic solvents. As a consequence most formulations containing these compounds are emulsion systems. As might be expected from their agricultural usage their mammalian and environmental toxicity profiles are quite benign. From an efficacy perspective they do not have as broad a spectrum of fungicidal activity as might be desired and little if any insecticidal activity. For this reason most of the wood preservative formulations in use today contain mixtures of triazoles or other fungicides with or without the addition of insecticides. For

example tebuconazole is used as co-biocide component in the ground-contact copper azole wood preservative discussed previously. Triazoles are also relatively poor performing compounds against mould and stain fungi.

Their efficacy against soft rot fungi is weak and as a result they are not usually used as the primary biocide in applications where softrot is a concern.

5.3.4. Quats: DDAC and ADBAC

Didecyldimethylammonium chloride (DDAC) and alkyldimethylbenzyl ammonium chloride (ADBAC) are quaternary ammonium compounds that are widely used as bactericides, antiseptics and fungicides. More recently the mainstream quaternary ammonium compounds used in wood preservative formulations have transitioned to chloride free products such as didecyl dimethyl ammonium carbonate ('carboquat'). The removal of the chloride ion reduces the corrosion characteristics of the quat. ADBAC, DDAC and DDAcarbonate can all be used as the 'quat' component of ACQ wood preservative formulations. DDAC is used as a component of anti-sapstain formulations. They are colourless, nearly odourless, and can be formulated for use with either water or oil-based carriers, although solvency is diminished in lighter aliphatic hydrocarbons such as mineral spirits.

Although quats can be used as stand alone wood preservatives in other parts of the world – especially in Japan – it is more common to see them used in combination with other fungicide or insecticide components for example with triazole fungicides or nicotinyl insecticides.

5.3.5. IPBC

3-Iodo-2-propynyl butyl carbamate (IPBC) is used in anti-sapstain formulations, or as a fungicide in water-repellent finishes for decks or siding. It is also used to treat millwork, and may be combined with azoles to enhance efficacy against mould fungi. IPBC may be used as either a solvent or water-based formulation. IPBC is colourless, and depending on the solvent and formulation, the treated wood may be painted. Protecting IPBC treated wood from direct sun light helps prolong its longevity as it appears that IPBC is somewhat susceptible to UV breakdown. Some formulations may have noticeable odour, but formulations with little or no odour are possible. IPBC is not an effective insecticide, and is not used as a stand-alone treatment for critical structural members.

Some pressure treating facilities use a mixture of IPBC and an insecticide such as permethrin or chlorpyrifos to treat structural members for above-ground end-uses that are largely protected from the weather. The advantage of this treatment is that it is colourless and allows the wood to maintain its natural appearance.

5.3.6. Zinc naphthenate

Zinc naphthenate is used as a component in over-the-counter wood preservative products. It can be formulated as either a solvent borne or waterborne preservative.

Unlike copper naphthenate, zinc napthenate imparts little colour, and thus is more compatible with finishes. When formulated in light solvent, the treated wood may be painted. However, wood treated with zinc naphthenate may have a noticeable odour and as a result it is not recommended for interior uses. Zinc is not as effective a fungicide as copper, and zinc naphthenate is not typically used as a stand-alone preservative for exposed structural members. However, zinc naphthenate does have some preservative efficacy, and may be sufficient to protect wood used above ground and partially protected from the weather. Zinc naphthenate pressure treatments have been shown to extend the life of treated stakes exposed in Mississippi, and brush treatments of a waterborne zinc naphthenate significantly improved the performance of pine fully exposed to the weather (above-ground) in Mississippi (Barnes *et al*., 2004). However, zinc naphthenate was less effective in protecting hardwoods in that above-ground study. The addition of a water repellent component to the treating solution appears to increase the efficacy of zinc naphthenate treatments.

5.4. Preservatives used in applications above ground and protected from liquid water

In general the primary threat in this end use category is insect attack, but protection against mould fungi or even decay fungi from occasional wetting may be desirable. Since liquid water is not an issue preservatives that do not fix in the wood can be used. They can be expected to provide adequate protection as long as the wood is not subjected to liquid water that could leach the active ingredients.

5.4.1. Borates

Boron has some exceptional performance characteristics including low mammalian toxicity, activity against fungi and insects, and low cost. A further advantage of boron is its ability to diffuse into green timbers that normally would resist traditional pressure treatment. Also, wood treated with borates has no colour and no odour

Borates are the most commonly used and versatile of the unfixed waterborne preservatives. They include formulations prepared from sodium tetraborate, sodium pentaborate and boric acid but the most common form is disodium octaborate tetrahydrate (DOT). DOT has higher water solubility than other forms of borate. Glycol is also used to increase solubility in some formulations.

Frequently wood is treated in the green condition. With greater mobility through heating and with higher solution concentrations, adequate core loadings of borate can be achieved by diffusion within a reasonable time frame (weeks). To avoid the long green diffusion times, there is a trend to partial drying before pressure impregnation. In conjunction with partial drying, DOT is able to penetrate relatively refractory species such as spruce using heated solutions, extended pressure impregnation periods and a subsequent diffusion soak. Pressure treated framing is used in areas of high termite hazard. With high retentions borates provide fire-retardant treatments for wood.

While boron has many potential applications, it is not suitable for applications where it is exposed to the weather, because borates are readily leachable. Therefore care must be taken to ensure that where borate treated wood is stored on site it is protected from precipitation. Research continues to develop borate formulations that have increased resistance to leaching while maintaining biocidal efficacy. Various combinations of silica and boron have been developed that appear to somewhat retard boron depletion, but the degree of permanence and applicability of the treated wood to outdoor exposures have not been well defined.

Also it is used as a surface treatment for a wide range of existing wood products such as log cabins, and the interiors of wood structures. Borates are also applied as internal or as remedial treatments using rods or pastes.

Another form of borate, zinc borate (ZB), is used as a preservative for wood-composite products. ZB as defined in American Wood Preservers' Association Standard P18 is 38.2% ZnO, 48.2% B_2O_3, and 13.6% H_2O. Zinc borate is a white, odourless powder with low water solubility that is added directly to the furnish or wax during panel manufacture. Zinc borate concentrations in the panel usually range from 0.75 to 1.5%. Because of its low solubility it does have some leach resistance once incorporated into the panel, and can be used in conditions with slight exposure to the weather if the panel is coated.

5.4.2. Insecticides

For interior uses protected from the weather decay or mould protection may not needed and wood may be treated with an insecticide only. Historically, insecticides with unnecessarily high mammalian toxicities such as lindane, dieldrin, aldrin and chlorpyrifos were used. More recently these have been largely replaced with pyrethroids such as permethrin and cypermethrin, as well as chloronicotinyl and neonicotinoids, pyroles, and insect growth regulators. These insecticides may also be incorporated with a fungicide, such as IPBC or the triazoles, to provide a greater degree of protection.

5.5. Non-biocidal approaches (see Chapter 4)

It is possible to impart a degree of durability to wood without the use of toxic components. Such treatments use strategies that limit water movement into the wood and/or render the wood structure unusable to degrading organisms. The simplest example is that of water repellents. Pressure treatments with high concentrations of wax greatly extend the service life of wood, even in ground contact (Crawford *et al*., 2002), but the loadings required are uneconomic.

Instead, interest is largely focused in two areas: wood modification and heat treatment. Both approaches are more expensive than conventional pressure treatments and historically their use has been limited. However increasing concerns about the environmental effects of biocides, and the increasing costs of the biocides themselves has made these alternative approaches more attractive. Apart from Europe, currently they are limited to niche markets.

5.5.1. Wood modification

The idea of wood modification is to make the wood both more moisture resistant and less attractive as a food source by replacing the cellulose and hemicellulose hydroxyl groups with other moieties (Evans, 2003). Various reactants have been considered, but the most common is acetylation. Acetylation, when applied with weight gains of 15-30%, results in more dimensionally stable wod. The ability of the wood to resist insect attack is less clear, and there is little or no protection against the growth of mould fungi. Due to the high weight gain required wood modification has not proved to be economically viable for broad scale usage, although in some niche markets such as flooring it has found some utility.

5.5.2. Heat treatment

The goal of heat treatment is to both volatilize wood components that are used as food by fungi and to alter the wood structure. Typically the wood is heated to 160-260°C. In one process the vessel is flooded with nitrogen, while another uses vegetable oil for rapid heat transfer. Decay resistance and dimensional stability are increased and the wood darkens to a brownish colour, making it suitable for some above-ground applications where appearance is important. Depending on the process, the wood suffers some loss in mechanical properties and so is not appropriate for critical structural applications. Heat treatments have gained popularity in Europe, where some of the most common wood species such as spruce are difficult to treat with preservatives. Research continues to optimize the trade-off between an increase in durability and losses in strength properties (Militz, 2002).

6. TREATMENT PROCESSES

A key to effective wood protection is to ensure that the active ingredient is present in a sufficient quantity and is well distributed within the treated wood. With some permeable softwoods this is a relatively simple exercise but with certain refractory softwoods and hardwoods getting the active components sufficiently deep into the wood to afford long term protection is a significant challenge. The treatment process used depends on the end use, the wood species, preservative characteristics, and the technology available. It is generally desirable that the wood is permeable so that the preservatives can penetrate readily.

6.1. Preparing wood for treatment

6.1.1. Green preconditioning

The ideal forest operation sees the lapse time between felling and milling reduced to a week at most. For somewhat longer periods limited protection can be provided by brushing or spraying the exposed end-grain of logs with a biocide such as copper-8 quinolinolate.

In some regions it is difficult to ensure a stable log supply due seasonal weather *etc*. Here short-to-medium term storage under sprinklers is a viable merchandising operation in the normal management of a forest. In more extreme instances, e.g. after a major storm, fresh windblown logs can be kept for some years submerged in ponds or under sprinklers (Figure 9.2a) that minimize oxygen and prevent growth of sapstain or decay (Liese, 1984). Anaerobic bacteria rapidly colonize these log piles and can selectively attack pit membranes, so improving permeability (Figure 9.2b). Impermeable Douglas fir sapwood can be treated with waterborne preservatives after sprinkling with a bacterial inoculum for a couple of weeks (Archer, 1985). Optimal conditions required incising when green to give the bacteria radial access to the full depth of the sapwood band at which point the bacteria migrated tangentially degrading pit membranes (Figure 9.2c). In many species however, the increased permeability is undesirable because it causes excessive preservative uptake.

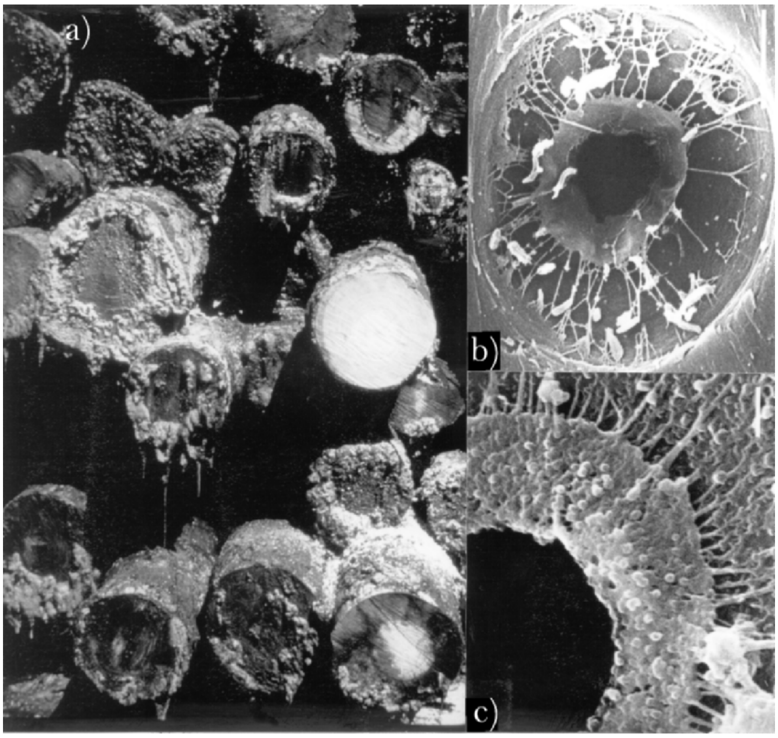

Figure 9.2. (a). Logpile in Balmoral Forest, New Zealand, five years after windblow (Liese 1984). A fresh exposed face, cut 100 mm from a log end, shows no stain or decay despite extensive surface colonization by microflora. (b) Douglas fir wood after several weeks under sprinklers show the complete disappearance of a central torus region: note the rod-shaped bacteria adhering to the relatively intact margo microfibrils (Archer, 1985). (c) Same material as in (b) emphasizing the doughnut appearance of the remaining torus, the intact margo and the granular material encrusting the pit chamber and torus (Archer, 1985).

6.1.2. Drying

As a rule, wood should be dried to its fiber saturation point or below before preservative treatment. Kiln-drying is common for dimension lumber, but the method of drying varies with climate and capital resources. For large timbers and railroad ties air-drying is used, despite the increased time required. However, in some climates it is difficult to air-dry material before it begins to suffer attack by stain fungi or even decay fungi, and alternative approaches must be considered.

Drying increases preservative penetration and also ensures, for larger timbers and roundstock, that much of the checking occurs before treatment. If timber is not adequately dried there is the risk that these checks might subsequently extend into untreated wood when the timber is in service. An alternative is to control subsequent checking through pre-treatments. One method for sawn or roundwood is to cut a saw kerf to the centre of the timber prior to drying and treating. As the wood shrinks, the kerf opens like a hinge to relieve the drying stresses.

Not all material needs to be dried, for example where the treatment relies on the diffusion of active ingredients through the green wood, or uses a pre-treatment schedule that removes water, e.g. steaming.

6.1.3. Incising

Some species, such as Douglas fir, larch and spruce, are very resistant to the penetration of preservatives and can only be pressure treated effectively if incised. In this case the wood is passed between toothed rollers (lumber) or through a cylindrical collar (poles) that contain adjustable steel knives (or needles) that incise the wood parallel to the grain (Ibach, 1999). The incisions are 6-20 mm long, about 3 mm wide and 12-24 mm deep (Figure 9.3), with the trend towards use of smaller, thinner teeth at closer intervals (Ruddick, 1987). Under pressure the preservative enters through the exposed end-grain in each incision and forms an envelope of treated wood that is slightly deeper than the incisions.

When treating poles, incisions can be concentrated on the region close to the groundline, so putting the preservative where it is most needed. Incising also promotes a more uniform checking pattern, with many small shallow checks spreading from the incisions rather than a few deep checks. The process causes a slight reduction in strength, especially if applied to dry wood or used on small dimension material (Winandy and Morrell, 1998).

6.1.4. Steaming or Boultonizing processes

With large members such as poles or piles thorough drying may be uneconomic and/or the members may get infected and begin to decay while drying. Steaming or Boultonizing is sometimes used to condition the green wood as part of the treatment process (Ibach, 1999).

In the steaming process, green wood is steamed in a pressurised treating cylinder for several hours, usually at a maximum temperature of 118ºC (245ºF) so that the

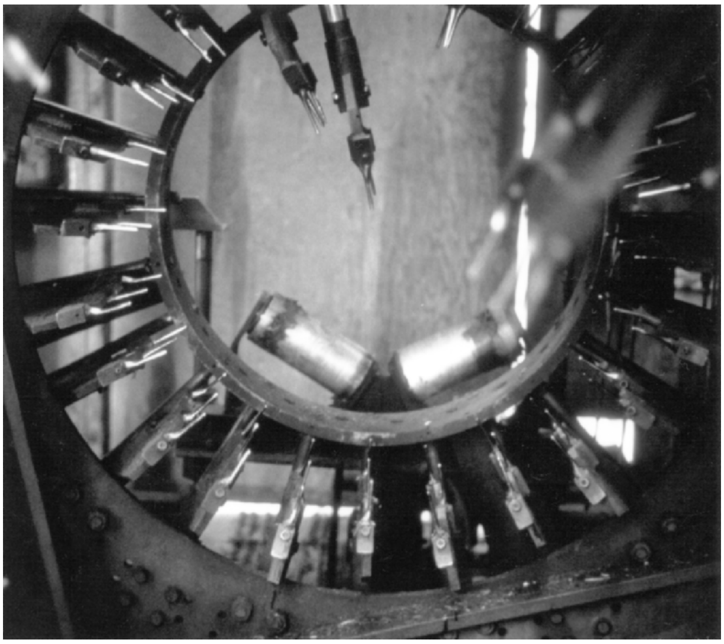

Figure 9.3. In the incising ring shown the needles can penetrate 20-60 mm and on subsequent treatment a preservative envelope of that depth forms in the impermeable timber. Deep incising is needed for demanding end uses, e.g. utility poles in the vicinity of the groundline.

outer annulus of wood is heated above 100°C. A sufficiently long steaming period also sterilizes the wood. Once steaming is completed a prolonged vacuum is applied. This generates a pressure gradient within the wood as moisture escapes as steam – largely through the ray tissue. The duration of the steaming and vacuum periods depend upon the size of members, the species, and moisture content. The boiling off of the superheated sap not only reduces the moisture content in the heated outer sapwood zone but also blows out unlignified ray tissue in some pines so that rays provide uninterrupted pathways for easy radial movement of the preservative solution: virtually every tracheid is connected to ray tissue. Steaming is much less effective where the ray tissue is lignified as in *Pinus elliottii*. The timber is left for a while to cool: this allows for moisture to redistribute: furthermore traditional CCA salts will precipitate out prematurely if the wood is too hot when pressure treated.

In the Boulton or boiling-under-vacuum method of partial seasoning, the wood is heated in the oil preservative under vacuum, usually at about 82ºC to 104ºC (180ºF to 220ºF). This temperature range, lower than that for the steaming process, is a considerable advantage in treating woods that are especially susceptible to collapse at high temperatures. The Boulton method removes much less moisture from heartwood than from sapwood. Both processes can result in strength losses to the treated wood if strict temperature and time limitations are not followed. Most countries have such limitations included in their treatment standards.

6.2. Vacuum/pressure impregnation treatments

Combined vacuum and pressure treatments are the most common methods of applying preservatives to wood. These techniques result in deep penetration of permeable timbers while at the same time controlling the amount of preservative retained. The process requires large heavy-gauge cylindrical pressure vessels up to 2 x 30 metres in size (Figure 9.4). There are a number of variations in the treatment schedules depending on the timber, preservative and intended end-use of the treated product (Hunt and Garrett, 1967; Nicholas, 1973b; Richardson, 1993).

6.2.1. Bethell (full cell) treatment

The distinctive feature of this treatment is the application of an initial vacuum (not less than -85 kPa) to draw much of the air out of the timber (Figure 9.5). The vacuum is held for at least 15 minutes. Then the preservative solution is drawn into the cylinder while maintaining the vacuum and when filled a hydraulic pressure is applied. Pressures up to 1575 kPa (225 psi) are common, with pressure periods varying from as little as 15 minutes to many hours. The pressure is maintained until the charge of timber is fully impregnated and/or the rate of absorption of preservative by the timber becomes negligible. At this point the preservative is drained from the cylinder and pumped back into the storage tanks. Since most of the air was removed during the initial vacuum high net preservative retentions are attainable with the full cell process. With a permeable timber the uptake of preservative can be in excess of 550 litres m^{-3} of timber, although a lower uptake is

Figure 9.4. CCA pressure treatment plant. The chemical storage tanks are out of sight.

common in refractory woods or in charges containing significant volumes of heartwood. Because the initial vacuum is unable to draw all of the air from the permeable wood a small amount will be trapped and compressed during treatment. When the timber is removed from the cylinder the compressed air can expand again gradually displacing some of the preservative from the timber charge. To avoid excessive kickback or bleeding a final vacuum (-85 kPa) is drawn for a few minutes before removing the timber from the cylinder. This process is most commonly used with water-based preservatives because the carrier (water) is inexpensive and because the solution concentration can be adjusted to achieve the desired retention of active ingredient within the wood.

6.2.2. Lowry (empty cell) treatment

With this method the aim is to achieve maximum penetration with a low net retention of preservative. No preliminary vacuum is applied before flooding the cylinder and an hydraulic pressure of up to 1575 kPa (225 psi) is maintained until the timber is fully treated (Figure 9.5). The pressure is released and a vacuum pulled to prevent excessive bleeding of preservative once the timber is removed from the cylinder. The compressed air re-expands displacing some of the preservative. With a permeable timber the net retention may only be 60% of the gross uptake, about 300 litres m^{-3} of timber. This process is useful for treating permeable timbers such as pine for exterior joinery and framing timber in low hazard situations. Subsequent drying is much shorter compared to the full cell treatment as considerably less moisture must be removed. The lower weight after treatment also reduces transport charges from the treating plant to the retailer or jobsite.

With some preservatives the temporary residence of the solution within the wood can result in partial fixation and in some cases selective absorption of one or more of the chemical components in the formulation such that the expelled solution ('kick-back') is no longer correctly balanced. Imbalance in the preservative solution needs to be monitored. Another undesirable characteristic of empty cell cycles is the fact the kick-back solution can contain dissolved wood sugars. These sugars can react with preservative components leading to the accumulation and deposition of insoluble precipitates, commonly referred to as sludge, in the bulk storage tanks.

6.2.3. Modified full cell or 'low weight' method

A method that combines aspects of both the full and empty cell treatment methods is now commonly used for treatment of permeable species with water-based preservatives. In a modified full cell treatment, the initial vacuum is of lower intensity and shorter duration than with a true full cell treatment. The pressure period is also shortened, while the final vacuum is of greater intensity and longer duration than the initial vacuum. This method yields adequate treatment with lower solution uptake than a full cell treatment. The wood gains less weight, reducing shipping costs. It is also less likely to drip preservative and has a much drier surface.

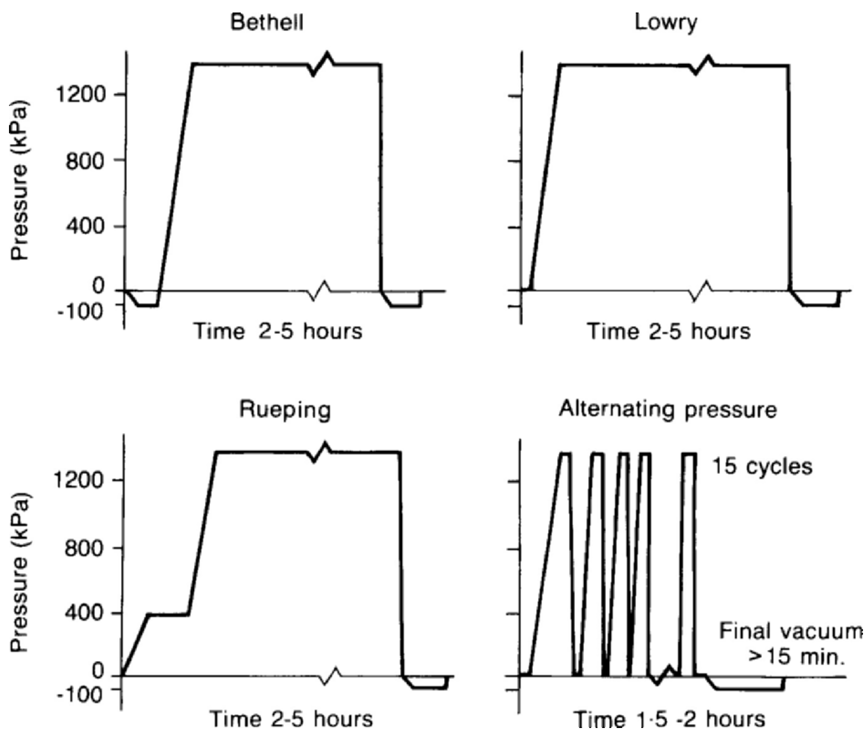

Figure 9.5. Time-pressure impregnation treatments.

6.2.4. Rueping process

This treatment is used principally with hot (>82°C) oil-type preservatives such as creosote and PCP where a low net retention is desired for some hazard categories. The treatment cycle begins with pressurizing the cylinder with air, no more than 700 kPa (100 psi) for creosote and PCP in oil (Figure 9.5). The preservative is pumped into the cylinder whilst maintaining pressure and when flooded the hydraulic pressure is increased to 1400 kPa (200 psi): species such as Douglas fir and larch are prone to collapse when the hot moist cells are subject to high pressures and the working pressure may have to be reduced somewhat (but still greater than 860 kPa). After the desired treatment time the pressure is released, the preservative is pumped back into the storage tank and a final vacuum pulled, again to minimize weeping. With a permeable timber the net retention is as low as 40-50% of the theoretical uptake, or about 220 litres m^{-3} of timber. Because creosote and PCP solutions are not usually diluted, adjustment of the initial air pressure and other treatment parameters is the primary method of obtaining a desired retention. This is an inexact method and it is difficult to produce material treated to a specified retention level.

6.2.5. Oscillating pressure method

Pressure treatments using waterborne preservatives require drying the wood before treatment and, in some case, again after treatment. Many pits aspirate when dried prior to treatment and the timber becomes less permeable. Redrying treated timber requires milder conditions as there is greater risk of steep moisture gradients and of checking. The oscillating pressure method utilizes repeated applications of high pressure and vacuum to force preservative into green wood so circumventing the problems arising from pit aspiration (Hudson and Henriksson, 1956). There is no pit aspiration prior to treatment and the timber need only be dried once – after treatment.

When a vacuum is applied the air in the tracheids expands and displaces some sap out through the rays to mix with the treatment solution in the cylinder. Some air is also expelled. When the hydraulic pressure is applied the air in the lumens is compressed and preservative solution is forced through the rays into the tracheids to mix with the sap. The cycle time is gradually extended to allow for the slower response deeper in the wood to the fluctuating pressure. This process was originally developed in Europe to treat unseasoned Norway spruce, *Picea abies*, and Scots pine, *Pinus sylvestris*, which are difficult to pressure treat with water-based preservatives. The treatment of large pole material took about 20 hours and involved numerous of treatment cycles; although where applied to more permeable species far fewer cycles and much shorter treatments times were needed. The method is not well suited to most current water-based formulations because the preservative reacts with sap displaced from the wood, causing sludging and surface deposits.

6.2.6. Vacuum treatments

With permeable wood species and members with small dimensions, a short vacuum or a double vacuum treatment may be sufficient to achieve the desired penetration (Table 9.3). In this process atmospheric pressure may be though of as the pressure period. Vacuum treatments have been commonly used for treatment of dry profiled or machined components (millwork) using preservatives carried in light organic solvents. The use of a volatile organic solvent avoids the dimensional swelling associated with aqueous treatments, and allows finishing within a short time after treatment. Although complete sapwood penetration is possible, this method emphasizes treatment of the end-grain where decay is mostly likely to occur in the exposed joinery. Organic preservatives containing azoles or IPBC are commonly used with this method. With permeable sapwood the uptake would be around 50 litres per m^3 of timber and with an impermeable hardwood using a more intensive schedule the solution uptake would be no more than 20 litres per m^3 of timber.

6.2.7. Other pressure treatment approaches

Certain timbers, such as some eucalypts which are highly impermeable to pressure impregnation, have been treated with varying degrees of success by resorting to very long treatment schedules or to the application of very high pressures, up to 7,000 kPa (1000 psi). Very high pressure treatments could only be considered for dense

timbers, otherwise the wood cells will collapse before the preservative penetrates the lumens (Tamblyn, 1978). The capital cost of such a treatment plant would be high.

There has also been research to evaluate the use of wood preservative treatment chemicals with supercritical CO_2 combined with appropriate co-solvents (Acda *et al.*, 1997). Although promising, this method would also require substantial capital investments in treatment plant equipment (Evans, 2003).

Another alternative is to re-examine the type of solvents used as carriers. Pressure treatments with a liquefied hydrocarbon gas can achieve much better penetrations especially in refractory timbers, because the viscosity of the liquefied gas is so low, about one fifth that of water in the case of butane. After impregnation the liquefied gas can be drained from the cylinder and that part which is retained in the wood can be evaporated off under reduced pressure. This process has the advantage of almost complete solvent recovery so that it is economic to select an expensive solvent which has optimum technical properties. The treatment gives a clean finish, except with certain timbers where there can be excessive exudation of resin which is solubilized in the butane. This treatment was originally conceived for treating with PCP but it is no longer used after significant in service failures were reported. While it was not anticipated at the time we now know that the oil carrier in traditional PCP treatments enhances the overall performance. The explosive flammability of the liquified gas was also a hazard, requiring the treatment cylinder to be flushed with nitrogen to remove any air. In some respects the underlying approach remains attractive but significant technical hurdles remain unresolved.

Table 9.3. Vacuum treatments using light organic solvents as carriers of the preservative (BWPA, 1986). The two schedules shown represent the extremes of treatment. The choice of a particular schedule is a function of the species, dimension of the material and the end use.

Increasing resistance of		Initial vacuum		Pressure phase		Final vacuum	
timber to impregnation		(kPa)	(min)	(kPa)	(min)	(kPa)	(min)
requires a severer, more	↓	-33	3	0	3	-67	20
prolonged treatment		-83	10	100	60	-83	20

.3. Non-pressure treatments

6.3.1. Brushing, dipping and soaking

The simplest treatment is an application by brush or spray. Although penetration across the grain is minimal, some penetration along the grain is possible. The additional life obtained by such treatments over that of untreated wood will be affected greatly by the conditions of service, e.g. just brushing untreated wood with a simple wax water-repellent is surprisingly effective for rustic joinery (Feist and Mraz, 1978; Feist, 1984).

Dip applications provide very limited protection to wood used in contact with the ground or under very moist conditions, and they provide very limited protection

against attack by termites. However, they do have value for exterior woodwork and millwork that is painted, not in contact with the ground, and exposed to moisture only for brief periods.

Dipping wood for even a few seconds will increase end-grain penetration somewhat beyond that achieved with brushing. In some cases, preservative in light solvent may penetrate the end-grain of pine sapwood by as much as 25 to 75 mm. Good end-grain penetration is especially advantageous for joints that are the most vulnerable point for decay in millwork products. However, if the wood is subsequently cut untreated end-grain will be exposed that needs retreating.

Soaking differs from dipping only in the amount of time that the wood is immersed. Members may be soaked for several hours and ever for many days, yielding substantial end-grain penetration. This process is still used in many parts of the world for the treatment of dried fence posts and small poles. Pine posts treated by soaking for 24 to 48 h or longer in a solution containing 5% of PCP in No. 2 fuel oil have shown an average life of 16 to 20 years or longer. The sapwood in these posts was well penetrated, and preservative solution retention levels ranged from 32 to 96 kg/m^3. Preservative penetration and retention levels obtained by soaking lumber for several hours are considerably better than those obtained by brief dipping of similar species, but still well below that obtained by pressure treatment.

6.3.2. Diffusion

Traditionally rough-sawn lumber is treated green off the saw where the moisture content is well in excess of fiber saturation (>50%). The moisture content is critical: even if only the surface has dried out briefly it becomes hydrophobic and does not pick up the solution (Dickinson and Murphy, 1989).

The boards are box piled, loosely strapped and immersed in a highly concentrated solution of boron salts for a few of minutes (Figure 9.6a). Alternatively timber on the green chain can be passed through a boron mist-spray tunnel or chain dip and then block stacked. The salt retention is a function of the surface area to volume ratio of the timber. Consequently thicker members may require a second dip 2-4 days later to fortify the salt concentration in the surface film. Once treated the timber is tightly wrapped and left for a number of weeks (Figure 9.6b). During this period the boron salts diffuse into the wood. The holding time varies from 4 to 6 weeks for 25 mm boards and up to 12 weeks for 50 mm stock, the time depending on the green moisture content and basic density of the timber (Barnes *et al*., 1989; Dickinson and Murphy, 1989).

After the holding period there is still a moderate concentration gradient across the material and a high overall loading of salt is needed in order to achieve a minimum core loading of 0.1% boric acid equivalent for softwoods and 0.2% boric acid equivalent for hardwoods in the centre of the timber. The eventual uptake of salts is controlled by such factors as:

- The concentration of the treating solution.
- The surface area to volume ratio of the timber.

- The temperature of the treating solution (the solubility of the boron salts increases with temperature, allowing more concentrated solutions to be used).
- The thickness of the solution film: for rough-sawn softwoods this is assumed to be about 0.2 mm, but with hardwoods and dressed softwoods the film is thinner.

Timber species can be grouped to take account of the fact that those having a high basic density and low green moisture content need to be immersed in stronger solutions in order to obtain the correct amount of preservative (wt/wt basis). Solution strengths vary from 15% to 45% of boric acid equivalent, but the more concentrated solutions can be achieved only by heating the solution above 50°C.

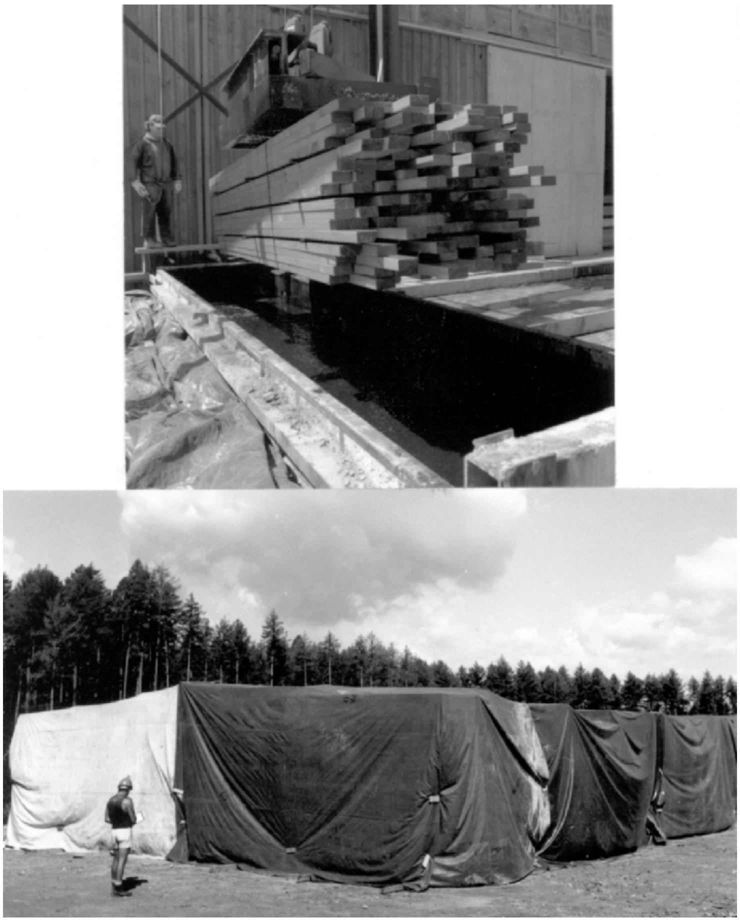

Figure 9.6. (a) Timber about to be immersed in a boron dip tank. Concrete drip storage area to the right. (b) Block stacked and covered timber is held for 4-8 weeks to allow salts to diffuse into the core.

The use of high molecular weight branched polymers as thickening agents results in a marked increase in the viscosity of the treatment solution (Vinden and Drysdale, 1990). In consequence a thicker film of boron salts clings to the timber and the vertical drainage of the salts through the block stacked timber is reduced. With thickened solutions there is much less within charge variability, less concentrated solutions are necessary and treatment times are reduced. Further it becomes possible to treat gauged timber so that there is no chemical loss or waste disposal problem as where rough-sawn timber is subsequently dressed.

The emphasis in Australia and New Zealand is on treating permeable pine, but diffusion treatments are effective with impermeable green hardwoods and softwoods such as hemlock and spruce. In tropical countries boron diffusion offers many advantages: no health hazard to operators, simple technology and the ability to treat local timbers locally. The major disadvantage is the stock holding period for diffusion and subsequent air-drying.

Today, just in time stock control favours a totally different approach, that of kiln-drying followed by pressure impregnation to obviate the long diffusion holding period.

6.3.3. Double diffusion

This process was suggested as an appropriate technology for developing countries. The double diffusion process consists of soaking green wood first in one chemical solution and then in a second solution (Johnson and Gonzalez, 1976). Because the chemicals are each water-soluble, they diffuse into the green wood, where they react to form leach-resistant compounds. In one scheme the wood is first soaked in a solution of copper sulphate ($CuSO_4$) for 1-3 days, and then soaked in a mixture of sodium dichromate ($Na_2Cr_2O_7$) or sodium chromate (Na_2CrO_4) and sodium arsenate (Na_2HAsO_4) for the same period (Markstrom *et al.*, 1999). In another scheme the wood is soaked first in sodium fluoride and then in copper sulphate. In theory, the first salt starts diffusing into the timber and as the other salts follow later they react with the first salt to precipitate out the non-leachable preservatives. However recent research with $CuSO_4$/NaF combination indictes that much of the fluoride remains leachanble after treatment (Morrell *et al.*, 2005). Another recent development involves partial air-drying and an initial hot soak (80-90°C) with the first salt, so that as the timber cools the partial vacuum encourages deeper initial penetration as the solution is drawn in by capillary tension. Consequently the salts used in the second dip have to diffuse further into the timber before the two chemicals react and precipitate out. With a hot soak or with thickening agents there will be less contamination of the second solution by the residues of the first solution still clinging to the wood surfaces. A negative to this method is the handling and dripping of preservative.

Despite the simplicity and elegance of the process it is hard to justify when used with such chemicals that have been restricted or withdrawn from general use in many developed countries.

6.3.4. Sap displacement (Boucherie process)

In the live tree there is a continuous conduction system within the outer sapwood. Thus water-soluble preservative solutions can be drawn up the tree after felling by immersing the butt in a solution of preservative – and relying on transpiration from the needles. Or, a freshly felled log can have its butt end elevated so that preservative can be introduced via a charge cap – a minimal hydrostatic head is all that is needed provided no air-water menisci intrude. More efficient systems use either vacuum caps to draw the preservative through the timber or pressure caps to force the preservative into the timber. No end-grain drying is permitted as air-water menisci require much greater forces to displace them through the capillary network in wood – dry ends of logs should be precut to re-expose green wood. These processes result in a preservative gradient within the roundwood, with the one end having a higher chemical loading unless the direction of flow is reversed. These processes are not commercial as there are problems of quality control, but they have uses in remote locations and where an on-farm treatment is desired. The displaced sap will contain some salts that are partially precipitated by reaction with the wood sugars. The expressed solution can be recycled or mixed with sawdust (to fix any residual chemical) and buried.

6.4. Treatment of wood composites

Some wood composite products such as plywood, glue-laminated beams, laminated veneer lumber, and parallel strand lumber can be treated using conventional pressure-treatment techniques. However, products made from smaller particles such as oriented strand board (OSB) or particle board may suffer significant losses in mechanical properties when pressure-treated. Even though they are used typically in dry environments, there is increased interest in protecting these panels from termite attack as well as from mould and decay fungi that may occur after unexpected moisture problems, for example in cases of building envelope failure (Gardner *et al*., 2003). Treated versions of these products incorporate preservatives such as zinc borate or copper ammonium acetate into the furnish or wax (Laks, 2004). In other cases an organic mouldicide such as IPBC/azole mixture is simply sprayed on the surface to provide temporary protection against mould during construction.

Another approach proposed for protection of composites is a vapour phase treatment (Murphy *et al*., 2002; Vinden *et al*., 1990). Certain esters of boron have high vapour pressures making them readily volatile and suitable for vapour phase treatment. For example trimethyl borate boils at 65°C so the treatment requires both timber and pressure vessel to be heated to at least this temperature. Trimethyl borate will react with the adsorbed moisture in the wood to yield methyl alcohol (which is recovered) and boric acid that remains in the wood:

$$B(OCH_3)_3 + 3H_2O \rightarrow H_3BO_3 + 3\ CH_3OH$$

Hydrolysis is virtually instantaneous, so in order to get deep penetration the wood must be very dry (<5-6% moisture content) otherwise most of the trimethyl borate

will react with the adsorbed moisture near the surface and the core will be deficient in boric acid. Such a low uniform moisture content is very hard to achieve, even in a kiln.

6.6. Wood properties affecting treatment

A basic knowledge of wood anatomy is helpful in understanding how wood structure affects the movement of preservatives through wood. The primary cell types in wood are tracheid/fibers (softwoods and hardwoods) or vessels (hardwoods) that can be thought of as collections of tubes oriented along the grain (Siau, 1984). Movement through these tubes (along the grain) is relatively rapid. Paths for movement across the grain are more limited, in which preservative must move through the relatively small pit openings between axial cells, or along the transversely oriented ray cells. Because ray cell are less numerous and shorter than the longitudinal cells, they do not provide for rapid movement across the grain of the wood. As a result, penetration of preservatives is usually many times greater along the grain than across the grain. But, because most wood products are very much longer than they are wide, adequate penetration is largely dependent on movement across the grain. Thus, it is the differences in paths of flow across the grain that causes differences in treatability. Much of this difference is attributable to the size, number and condition of the pit openings. Generally pines are easy to treat because the ray cells have very large openings between cells, whereas spruces and Douglas fir have very small openings. Between ray cells and longitudinal fibers, pines can have very large window pits (pinoid) whereas spruces have very small pitting between ray cells and longitudinal fibers (Panshin and deZeeuw, 1980).

Some species have notable differences in penetration between earlywood and latewood bands of the annual growth ring. Latewood cells with thicker walls mean the pit membranes are less likely to aspirate and permeability can remain high. This differential treatability sometimes results in a ‘zebra’ treatment with alternating bands of treated latewood and untreated earlywood.

The ratio of sapwood to heartwood volume in a tree species is also a key to its treatability. In most species sapwood is more permeable than heartwood; and in some species, such as many pines, the difference is very great. In the heartwood there is a higher proportion of extractives, which block the ray cells and encrust pit membranes. The pit membranes are also lignified and often aspirated. Thus the perceived treatability of a species may be largely a function of the proportion of sapwood in lumber cut from that tree. Many pine species, such as the southern pines, have a large sapwood band that results in a larger proportion of treatable sapwood in most lumber dimensions. Conversely, Douglas fir has only a thin sapwood band and most material cut from this species contains substantial heartwood. In other species, such as spruce, the sapwood and heartwood are both difficult to treat with the heartwood being only slightly more impermeable than the sapwood. Although heartwood is often more naturally durable than sapwood, a wide permeable sapwood band is preferred for many uses since the durability of treated sapwood can be considerably greater than that of untreated heartwood. The difficulty in treating

heartwood has led to the practice of calculating the preservative retention on the basis of the volume of sapwood in the treatment charge. The sapwood content can vary widely and is often much less than the volume of untreatable heartwood. In some cases it has been recommended that the specified retention should consider not just the volume of treatable wood but also the amount of treatable wood (volume x basic density), with denser material requiring a higher preservative loadings.

Hardwoods have a more complex structure than softwoods, and penetration and distribution of preservative is often adversely affected. The main flow paths are provided by vessels. Connections between vessel elements are efficient but the vessels themselves have limited length. Some species have a very intensive branching and interconnecting system (*Fagus* spp.), in others vessels are very straight with few interconnections (*Eucalyptus* spp.). Further there is limited flow to adjacent fibres. The proportion of vessel tissue in hardwoods is also variable, ranging from 15-50%. Although tyloses can occur in sapwood they are much more abundant in heartwood and dramatically reduce its permeability. Tyloses are found in about half of all hardwoods. Other species secrete resin and gum exudates to seal the vessels.

Penetration will be poor if the vessels are blocked by tyloses, if there are too few vessels, or if the vessels are too small. Ring-porous hardwoods have much larger vessels in the earlywood than in the latewood. For example, *Eucalyptus delegatensis* has no vessels in the latewood in which to adsorb preservative. There is little evidence of lateral movement of creosote within eucalypt wood and the vessels are sharply defined by their preservative content. Also with CCA salts the distribution is non-uniform with copper salts tending to remain in or near the vessels. Such material can fail in ground contact despite having high preservative loadings as the poor preservative distribution means that fungi can attack the untreated fibres away from the immediate vicinity of the vessels. However the susceptibility of hardwoods to soft rot fungi is not simply a matter of poor distribution of preservative, rather hardwoods are better utilized by these fungi. Soft rots tolerate greater amounts of preservative where the substrate is highly nutritive and can support good growth.

It should be emphasized that world-wide the treatment industry is based on comparatively few moderately permeable timbers. Problems can arise when there is commercial interest in using a timber that is somewhat less than ideal, perhaps because it is the main plantation species of that country (for example in the use of eucalypts and spruce). Although treatment of refractory species is not ideal, by drying to a low moisture content and with a high preservative loading in the surface layer, adequate service life may be achievable for certain end uses.

6.7. Remedial treatments

There is substantial interest in using preservatives to extend the life of treated wood that is already in service (Barnes *et al*., 1995; Morrell *et al*., 1996). These remedial treatments are most economic for high-value products that are expensive to replace, such as utility poles, piles, and bridge timbers. However, they are also used to protect log cabins, fence posts and millwork.

In utility poles the treatments fall into two categories: those intended to protect the untreated heartwood; and those intended to fortify and replenish the preservative in the sapwood around the groundline area. Treatment of the internal areas in a pole are usually accomplished by drilling holes at a 45° angle downward into the pole. A liquid or solid preservative is then placed in the hole and the hole is plugged. Preservatives for internal treatment of poles commonly contain a fumigant ingredient such as methylisothiocyanate (MITC), although boron and fluoride rods are also used. Piles and bridge timbers may be treated internally in a similar manner. External treatments are applied to poles by digging the soil away from the base of the pole and applying a paste or bandage to the groundline area. Copper and boron are the most common ingredients in these groundline treatments.

Remedial treatments for log cabins and millwork are applied generally by drilling holes into the member and adding a diffusible borate preservative. Borates have been formulated as rods, pastes, thickened solutions and powders for this type of application.

7. HEALTH AND ENVIRONMENTAL ISSUES

Wood preservatives must strike a balance between beneficial toxicity towards wood-attacking organisms and potential harm to non-target organisms. Because a wide range of organisms can attack wood, the most versatile wood preservatives must have a broad-spectrum toxicity. It is almost inevitable that preservatives that protect against a wider range of wood attacking organisms also have the greatest potential for harming non-target organisms. This is the situation with the traditional broad-spectrum preservatives such as creosote, PCP and CCA.

The shift to preservatives based on copper, azoles, and quaternary ammonium compounds has lessened the risk associated with wood preservatives. However, all wood preservatives contain ingredients that pose some degree of risk to non-target organisms, and the public and regulatory perception of a proper balance between risk and benefit is steadily changing (Brooks, 2002; Lebow *et al.*, 2002). Preservative ingredients that are considered acceptable today may be considered as less desirable in the future.

Perhaps the greatest health and environmental risks with wood preservatives occur at the treatment plant. Here, improvements in handling and containment technologies have greatly lessened these risks at modern treatment facilities. Now, more concern has shifted to end-use, where risks may be encountered by construction personnel, consumers and the environment. Where still allowed, the use of creosote, PCP and inorganic arsenical preservatives is usually limited to high degradation hazard applications where direct human contact is minimized. In high contact areas such as residential decks or buildings, these preservatives have been replaced with formulations containing ingredients with lower mammalian toxicity such as copper, azoles and borates. Concerns about environmental impacts, especially in aquatic environments, are also associated with treated wood applications.

Restrictions on use of creosote and arsenical preservatives have been proposed in some areas despite relatively little evidence of environmental impacts (Brown *et al.*, 2003). Because there is little evidence of traditional preservatives causing harm to the environment, it is difficult to establish that the alternative treatments are less harmful. However, it is apparent that some release of preservative occurs from all types of treated wood and that treatment and processing practices can be adapted to minimize these releases (Cooper, 2003; Lebow and Tippie, 2001).

7.1. Over-treatment and re-treatment

In most parts of the world preservative retentions in common use are specified by wood preservative standards which are in turn backed by scientific studies. Wood treated to a standard, combined with third party quality audit inspection schemes, can be expected to provide consistent performance appropriate for the intended application. It is common practice for standards to prescribe minimum retention and penetration levels as opposed to maxima. If the goal is to maximise the longevity of preservative treated wood this approach might at first seem counterintuitive. But where the broader picture is taken into consideration, increasing the retention based on the premise that 'more must be better' needlessly increases the amount of leachable chemical in the wood without necessarily providing a durability benefit. It is rarely good practice to ask for a retention higher than that specified in wood treatment standards. A similar concern arises with the practice of retreatment of charges that originally failed to meet penetration or retention requirements. Although retreatment of failed charges is acceptable in some situations, it can lead to increased bleeding or leaching of excess preservative. The modern approach to these issues relies on best management practice concepts that define pretreatment, treatment and post treatment handling of treated wood products.

7.2. Bleeding of oil preservatives

Oil-type preservatives sometimes bleed or ooze to the surface of the treated wood. This may be apparent immediately after treatment. More problematic bleeding may occur in service in a location where it is exposed to direct sunlight: dark wood can get very hot. Now the problem is harder to remedy. This issue is best addressed through strict control of treatment processes. Processes used to reduce bleeding include:

- Maintaining clean facilities and working solutions.
- Avoiding over-treatment.
- Using post-treatment conditioning techniques such as final vacuum, steaming, and expansion baths.

Typically the volume of preservative that oozes out of the wood into the environment is quite small, but it can appear much larger if it spreads on the surface

of standing water. Wood with a visibly oily surface should not be used for projects in sensitive environments or in applications likely to involve human contact, i.e. decking and handrails.

7.3. Fixation of water-based preservatives

The active ingredients of various waterborne wood preservatives, i.e. copper, chromium, arsenic and/or zinc, are initially water-soluble in the treating solution but become resistant to leaching when absorbed in the wood. This leach-resistance is a result of the chemical 'fixation' reactions that render the toxic ingredients insoluble in water. The mechanism and requirements for these fixation reactions differ depending on the type of wood preservative (Bull, 1998). For each type of preservative, some reactions occur very rapidly during pressure treatment, while others may take days or even weeks to reach completion, depending on post-treatment storage and process conditions. If the treated wood is placed in service before these reactions are completed, the initial release of preservative into the environment may be many times greater than for wood that has been adequately conditioned. Concerns about inadequate fixation have led Canada and European countries to develop standards or guidelines for 'fixing' treated wood, and similar efforts are underway in the United States (Cooper, 2002; Pasek, 2003).

The essence of CCA-C fixation is the reduction of chromium from the hexavalent to the trivalent state, and the subsequent precipitation or adsorption of chromium, copper and arsenic complexes in the wood substrate. Some of these reactions, such as the adsorption of copper and chromium onto the wood components, occur within minutes or hour while others are completed during the ensuing days or weeks. The length of time needed for fixation is greatly dependent on temperature, and the reactions may proceed slowly when the treated wood is stored out of doors in cool weather (Cooper, 2000). Because fixation at ambient temperatures may be unacceptably lengthy, several techniques are used or have been proposed to elevate the wood temperature and accelerate fixation, including various forms of kiln-drying, hot water baths and steaming. These accelerated fixation methods are quite effective, although care must be taken not to dry the wood too quickly or to elevate the temperature to a level that may harm the mechanical properties of the wood.

In ammoniacal systems the metals are solubilized by ammonia, and become insoluble as the ammonia evaporates. Some of the metals appear to simply precipitate within the wood, while others react with the wood structure (Lebow and Morrell, 1995). Volatilization of ammonia appears to be a key factor in fixation with ammoniacal preservatives, and this can be accomplished by air-drying, kiln-drying, or a combination of both. Placing stickers between layers of wood greatly increases the rate of drying of the treated wood. Until recently the fixation processes of the amine wood preservatives were poorly understood but ongoing research in North American university laboratories is beginning to expand the knowledge base considerably. At low retentions the bulk of fixation appears to occur very rapidly, within a few hours after treatment. At higher retentions, however, fixation is slower and temperature dependent (Ung and Cooper, 2005).

7.4. Recycling and disposal

A significant challenge facing treated wood products is the lack of an effective strategy for handling treated wood that has been removed from service (Connell, 1999). Currently, much treated waste wood is either placed in landfills or stockpiled waiting disposal. Land filling certain types of treated wood is restricted in some countries and under close scrutiny in others because of concerns about groundwater contamination. The potential environmental impact from treated wood in landfills is debatable; but the lack of strategies for reuse or recycling treated wood is clearly a legitimate concern. Several obstacles have been difficult to overcome in managing treated wood waste. For treated wood used in residential construction, one of the greatest difficulties is the lack of an efficient process for collecting and sorting treated wood (Smith *et al*., 2002; Solo-Gabriele and Townsend, 1999). This is less of a problem for products such as railroad ties and utility poles.

Once collected, a number of options have been proposed for reuse or recycling of treated wood. Reuse is a desirable option as long as the secondary use is appropriate for that product. Used railroad ties are often reused as fence posts or landscape timbers, and utility pole are reused for fence posts or bridge supports. The proportion of wood treated with heavy metals that is reused is smaller, again in part because of problems with collecting and sorting. Appearance is also an issue, because many of these products are used in residential applications.

Researchers have demonstrated that wood treated with heavy metals can be chipped or flaked and reused to form durable panel products or wood-cement composites. However, this type of reuse has not gained commercial acceptance because of concerns with processing the treated wood, with the introduction of pesticides into the panel fabrication process, and with the leaching or environmental impacts from the final product (Kartal and Clausen, 2001).

Another viable option for products treated with creosote and PCP (and presumable other organic treatments in the future) is burning to generate power (cogeneration). When added as a small percentage of the overall fuel load these types of treated wood can be burned without unduly increasing air emissions. As fuel costs and energy demands increase, disposal of treated wood in this manner becomes more attractive.

The direct extraction and reuse of the metals from treated wood has been proposed. These include acid extraction, fungal degradation, bacterial degradation, digestion, steam explosion, or some combination of these techniques. All of these approaches show some potential, but none are currently economic (Helsen and Van den Belk, 2005).

Cogeneration poses additional challenges for wood with heavy metals – particularly for wood treated with arsenic. As well as concerns with emissions, the concentration of metals in the ash requires further processing (Solo-Gabriele *et al*., 2002). Various processes have been proposed to extract and reuse the metals from the ash, but when combined with challenges in collection and sorting, the economics of these processes become daunting (Bull, 1998).

Nurmi and Lindros (1994) had the ingenious scheme of feeding treated wood chips into the smelting furnace at a copper smelter. This causes no difficulties since

copper ores contain arsenic and other heavy metals, and both copper and arsenic are recovered.

In most situations disposal in designated landfills is deemed sufficient – as well as being the least expensive option – but others may require immobilization in concrete.